Sym. on Thermal Radiation of Solids, San Francisco, Calif., Mar. 4-6, 1964, Sponsored by the Univ. of Calif.

22p

X64 10034

Code 2A

EFFECTIVENESS OF SOLAR RADIATION SHIELDS FOR THERMAL CONTROL OF SPACE VEHICLES SUBJECTED TO LARGE CHANGES IN SOLAR ENERGY

(NASA TM X-51040)

By John C. Arvesen

NASA Ames Research Center, Moffett Field, Calif.

John C. Arvesen [1963] 22p refs For presentation at the Symp. on Thermal Radiation of Solids, San Francisco, Mar. 4-6, 1964 10034

SUMMARY

The effectiveness of a solar shield in providing thermal control of a sun-oriented space vehicle traveling from the earth to within 9 million miles (~0.1 astronomical unit) from the sun is studied. Experimental temperature changes of the shielded vehicle are compared with predicted values obtained from a previously developed radiative heat-transfer analysis. The capsule tested was conical in shape and the shield was a flat disk. The shield was placed at a given distance from the capsule and completely shaded the capsule from an infrared radiation source. The shields were heated by the source to a predetermined temperature representative of a certain distance from the sun. The tests were conducted in a 4- by 5-foot vacuum chamber at a pressure of less than 5×10^{-6} Torr. The walls of the chamber were blackened and cooled with liquid nitrogen to simulate the thermal environment of space.

The temperature rise on the capsule resulting from an increase in shield temperature is shown to be a function of the radiation configuration factors between the shield and the capsule, the total hemispherical emittances of the shields and capsules, and the internally generated heat. The necessity of considering the angular absorptance characteristics of the capsule is also discussed. Results indicate that with shields and with constant internal power, the change in capsule temperature can be held to about 10° F for a shield temperature increase of 1000° F. This shield temperature increase is consistent with an approach to within 9 million miles of the sun with a reasonable shield configuration.

AUTHOR

INTRODUCTION

The exploration of interplanetary space and of the planets will require the use of spacecraft with ever increasing sophistication and complexity. The temperatures of instrumentation and equipment on such spacecraft will probably have to be maintained within limits which are even more stringent than those currently needed.

The temperature control of such vehicles is therefore a significant problem, especially for those missions in which the intensity of the incident solar radiation increases substantially. At the orbit of Venus, for example, the solar radiation intensity is approximately 1.9 solar constants (i.e., 1.9 times the intensity at the earth's distance from the sun). For a mission to Mercury, the intensity increases to about 6.6 solar constants. A feasibility study has indicated that a solar probe which would approach to within 9 million miles (0.1 A.U.) of the sun could also be a worthwhile scientific mission. (See ref. 1.) For this mission, the maximum intensity would be 100 solar constants.

Based on the requirements for the solar probe mission described in reference 1, an analysis was made (ref. 2) in which the concept of solar radiation shields was developed as a method of achieving satisfactory temperature control for a sun-oriented capsule subjected to large changes in radiation intensity. This study indicated that in going from 1.0 to 0.1 A.U., the temperature rise would be no more than 26° and 2° F, respectively, for conical capsules with single and double radiation shields. This would compare with a temperature rise of hundreds to thousands of degrees, depending on surface properties, for an unshielded capsule. This significant reduction in capsule temperature rise with solar shields was based on an analysis which included some simplifying generalizations and assumptions. It was therefore pertinent to substantiate the analytic results with experiment. The purpose of this paper is to present the results to date of this experimental program and to show how these results compare with those obtained from the analysis of reference 2.

EXPERIMENTAL PROCEDURE

Because of the lack of a suitable source of solar radiation for duplicating the solar intensity at 0.1 A.U. (100 solar constants), the solar shields used in the experiments were heated with infrared radiation. However, the resultant temperatures of the shields can be directly related to distance from the sun with a minimum number of assumptions. The main problem in the analysis of shield-capsule configurations is the prediction of the radiation heat transfer between the shield and capsule and the resultant capsule temperature. Fortunately, this problem can be readily studied experimentally since the source used in heating the shields is immaterial.

Models

Tests were conducted on shield-capsule models having the same geometry as the "solar-probe configuration" studied analytically in reference 2. A schematic drawing of this configuration is shown in figure 1 and a photograph of a typical capsule model, with thermocouples and power leads attached, is shown in figure 2.

The conical-capsule models were 1 foot in length and 6 inches in diameter, with a resulting semiapex angle of about 14°. They were constructed of 1/32-inch-thick aluminum. Heat was generated internally by an electrical resistance heater. Conduction of heat to or from the capsule models through the heater-power leads was minimized by the use of guard heaters at the same temperature as the capsule.

The shields were 6 inches in diameter (shield diameter = cone base diameter) and were constructed of 1/16-inch-thick aluminum.

Two different model surfaces were tested. One was polished aluminum and the other was a carbon-black coating. The aluminum surface reflected incident radiation specularly and absorbed and emitted radiation in an angularly dependent or nondiffuse manner. (Directionally dependent emittance and absorptance properties are characteristic of polished metals, e.g., see ref. 3.) The carbon-black surface absorbed and emitted radiation in a diffuse manner. The experimentally determined differences between the two types of surfaces are shown in figure 3. In this figure, it is to be noted that the carbon-black surface has the same emittance at all angles while the emittance of the aluminum surface depends on the angle.

Test Apparatus

A 4-foot diameter by 5-foot long vacuum chamber was used in the tests. Photographs of this chamber are shown in figure 4. The tests were conducted at a pressure of 5×10^{-6} Torr. All convective heat transfer is, therefore, negligible.

A cold-wall assembly, consisting of a double-walled cylinder and two double-walled end sections, is located within the vacuum chamber. This assembly is cooled to -320° F by liquid nitrogen. The interior of the assembly has a black coating with an infrared absorptance of 0.94. The exterior is wrapped with an aluminized mylar "superinsulation" to reduce the heat input from the vacuum-chamber walls to the cold wall assembly. The working space within the chamber is 3 feet in diameter and 4 feet long.

The shields are heated by infrared radiation to a uniform, predetermined temperature by means of a two-element electrical radiative source. The back of this heater is surrounded by a liquid-nitrogen-cooled shroud to eliminate stray thermal radiation inside the cold walls due to radiation from the heater. A schematic diagram of a typical experimental test setup is shown in figure 5.

Auxiliary Equipment

Additional equipment was required to monitor the temperatures of the capsule and shield models, to supply and measure the capsule internal heat, and to determine the emittance of the aluminum and carbon black surfaces of interest.

Temperatures on the models were measured by thermocouples located at various points on their surfaces. The thermocouple readings were recorded on a strip-chart recorder. To verify, within a reasonable time, that thermal equilibrium had been established, it was necessary to monitor very small temperature changes. These changes were determined by nulling the output voltage of the thermocouple with a known voltage.

The electrical power to the resistance heaters within the capsules was supplied by a regulated d-c power supply. The power to the capsule was determined by measuring the voltage across the input terminals to the capsule and the voltage drop across a known resistance in series with the leads.

Test Procedure

The total hemispherical emittance of the capsule's surface was determined by a heat balance on the unshielded capsule model when heated internally to a predetermined temperature in the vacuum chamber. The technique involved is the same as that presented in reference 4. The shield was then placed at a specified distance from the capsule and the capsule's temperature adjusted by its internal heater to approximately 70° or 80° F. The shield was next heated to a certain temperature and then held constant. The increase in temperature of the capsule was monitored and its temperature at equilibrium recorded. The temperature of the shield was increased in steps up to $\sim 950^\circ$ F and the corresponding equilibrium capsule temperatures were determined.

ANALYSIS

In this section, those equations from reference 2 which are pertinent for comparison with the experimental results are presented in simplified form. In addition, some discussion is given of those factors or parameters which contribute to temperature control of a solar-radiation-shielded capsule.

Unshielded Vehicles

For a vehicle in space, the only mode of heat transfer to the surroundings is by radiation from the outside skin. This radiation is governed by the Stefan-Boltzmann law, that is,

$$Q_{radiated} = \epsilon_c A_c \sigma T_c^4 \tag{1}$$

where

ϵ_c capsule emittance

A_c capsule surface area

T_c capsule temperature

σ Stefan-Boltzmann constant

At thermal equilibrium

$$Q_{absorbed} = Q_{radiated} \tag{2}$$

The heat absorbed by a vehicle's surface results from two sources; one from the external environment and one from the vehicle's internally generated heat:

$$Q_{absorbed} = Q_{external} + Q_{internal} \tag{3}$$

The external radiation absorbed when the sun is the only source is

$$Q_{external} = \alpha_{sc} \frac{E}{r^2} A_x \tag{4}$$

where α_{sc} is the solar absorptance of the vehicle's surface, E/r^2 is the solar flux at a distance r from the sun (E is the solar constant) and A_x is the projected surface area normal to direct solar radiation.

For the idealized case of uniform surface temperature, the heat balance at thermal equilibrium may be written as

$$\alpha_{sc} \frac{E}{r^2} A_x + Q_i = \epsilon_c A_c \sigma T_c^{\,4} \tag{5}$$

which, when solved for T_c, gives

$$T_c = \left(\frac{\alpha_{sc} \frac{E}{r^2} A_x + Q_i}{\epsilon_c A_c \sigma} \right)^{1/4} = \left[\frac{\alpha_{sc}}{\epsilon_c} \left(\frac{E}{r^2} \right) \left(\frac{A_x}{A_c} \right) \left(\frac{1}{\sigma} \right) + \frac{Q_i}{\epsilon_c A_c \sigma} \right]^{1/4} \tag{6}$$

where $Q_i = Q_{internal}$

Shielded Vehicles

A simple shield-capsule configuration, such as shown in figure 1, has been chosen to illustrate the degree of temperature control that can be achieved with solar radiation shields. The methods developed in reference 2 to analyze the radiation heat transfer and equilibrium temperatures for shielded capsules are involved and lengthy. Thus, only the pertinent expressions and results from this reference will be presented herein.

For purposes of illustration, an expression for the temperature of a singly shielded capsule as a function of the temperature of the shield is derived to show the relationship of the radiation heat-transfer parameters. For the configuration chosen, reflections between capsule and shield can be neglected.

For a shield of temperature T_1, the radiation emitted from the shaded side (side 1b) is

$$Q_{radiated} = \epsilon_{1b} A_1 \sigma T_1^{\,4} \tag{7}$$

The radiation from the shield that is incident upon the capsule is

$$Q_{incident} = F_{1b-c}\, \epsilon_{1b} A_1 \sigma T_1^{\,4} \tag{8}$$

where F_{1b-c} is a radiation configuration factor defined as the fraction of the total radiation emitted from surface 1b that is incident upon the capsule (for the configuration studied $F_{1b-c} = 0.048$, as determined in ref. 2). The amount of this radiation that is absorbed by the capsule is

$$Q_{absorbed} = \alpha_c F_{1b-c} \epsilon_{1b} A_1 \sigma T_1^4 \tag{9}$$

where α_c is the fraction of the radiation incident upon the capsule that is absorbed. (α_c may be dependent upon the angle of incidence on the capsule of the radiation received from the shield, as shown in fig. 3.) The heat balance on the capsule is then

$$\alpha_c F_{1b-c} \epsilon_{1b} A_1 \sigma T_1^4 + Q_i = \epsilon_c A_c \sigma T_c^4 \tag{10}$$

The temperature of the capsule as a function of the shield temperature is, therefore, given by

$$T_c = \left(\frac{\alpha_c F_{1b-c} \epsilon_{1b} A_1 \sigma T_1^4 + Q_i}{\epsilon_c A_c \sigma}\right)^{1/4} \tag{11}$$

The shield temperature at distance r from the sun is given by

$$T_1 = \left[\frac{\alpha_{s1a} \frac{E}{r^2}}{(\epsilon_{1a} + \epsilon_{1b})\sigma}\right]^{1/4} \tag{12}$$

where the subscript 1a refers to the sunlit side. Thus, by specifying the solar absorptance and thermal emittance properties of the sunlit side of the shield, an experimentally determined change in capsule temperature as a function of shield temperature can be related to distance from the sun.

RESULTS AND DISCUSSION

Thermal problems associated with unshielded vehicles which approach the sun are first discussed. The calculated effect of placing a disk shield between the vehicle and the incident solar radiation is next presented. The results of the calculations are then compared with the experimentally determined results.

Unshielded Vehicles

The problem of thermal control of an unshielded vehicle during an approach to the sun is illustrated in figure 6. In this figure, the temperature of a conical capsule (low ratio of A_X/A_C) is given as a function of distance from the sun for various ratios of solar absorptance to emittance (α_S/ϵ). Also shown on the figure is an arbitrary temperature range of 60° to 90° F within which the vehicle should probably be maintained from an instrumentation and equipment standpoint. Even for the lowest value of $\alpha_S/\epsilon = 0.2$ (which is near the minimum achievable with engineering materials), the temperature becomes undesirably high when the distance from the sun is less than 0.33 A.U. For all values of α_S/ϵ the temperature of the capsule increases rapidly as the distance from the sun is decreased.

Shielded Vehicles

Theoretical capsule temperatures as a function of distance from the sun were calculated from the equations given in the Analysis section based on the results of reference 2. These calculations are presented in figure 7 for the two configurations studied. For purposes of illustration, the "sunlit side" of the shield was assumed to have a white coating. The analytical results indicate that when the "backside" is black and the capsule is black, the vehicle can approach to within 0.11 A.U. from the sun, and when the backside is aluminum and the capsule is aluminum, the vehicle can approach to within 0.04 A.U. from the sun without exceeding a 30° F rise in capsule temperature. For each configuration the capsule's internal heat is constant but the magnitude is determined by the heat necessary to achieve a capsule temperature of 60° F at 1 A.U.

The corresponding calculated temperatures for the shield (based on equation (12)) are given in figure 8 for the surface properties considered. A comparison of figures 7 and 8 shows that the shield temperature varies substantially more than the capsule temperature for a given change in distance from the sun. It should be emphasized that, for given shield properties, the shield temperature has a definite relationship with distance from the sun. As will be shown, this fact is utilized in the evaluation of the experimental results in terms of a solar probe mission.

Experimental Results

Capsule temperatures as a function of shield temperature were determined experimentally for the two configurations tested. The total hemispherical emittance of each surface material was determined by a heat balance on the unshielded capsule model. This measured emittance was used as the basis by which the calculations of capsule temperature change were compared with the experiment.

Black shield and black capsule.- Experimentally determined capsule temperatures at various shield temperatures for the shield-capsule model with diffuse, black surfaces are shown in figure 9. As the temperature of the shield was increased to ~950° F, the temperature of the capsule increased from 73° to 116° F as a result of absorbed radiation from the shield. The experimental and predicted temperature change agreed within 6 percent, indicating that the mathematical techniques of the analysis are satisfactory and that the necessary assumptions are justified for the configuration with carbon-black surfaces.

Aluminum shield and aluminum capsule.- Results for the aluminum configuration are shown in figure 10. Increasing the shield temperature to 980° F increased the capsule temperature from 81° to 91° F. However, in this case, the calculations predicted only a 4° F increase for the same change in shield temperature. The discrepancy is not excessively large on an absolute basis (6° F), but amounts to an error of 150 percent in the prediction of the change in capsule temperature.

The calculated radiation factor between the shield and capsule was shown to be correct by the closer agreement between theory and experiment for the diffuse, black configuration. The total hemispherical emittances of the aluminum shield and the aluminum capsule were verified by radiometric measurements to be very nearly the same (as was assumed). It was therefore concluded that the probable cause of the discrepancy was the nondiffuse characteristics of the aluminum surfaces. In the calculations, the absorptance of the aluminum capsule was assumed to equal its measured total hemispherical emittance ($\alpha_c = \epsilon_c = 0.067$). As was shown in figure 3, however, the aluminum surface exhibits a very strong absorptance at high angles of incidence (viewing angle, $\varphi > 50^\circ$). For the shield-capsule geometry studied, this angular dependence will mean that the actual absorptance of the capsule to radiation from the shield could be much higher than the total hemispherical emittance measured, since the angle of incidence for the capsule is very high. To make a quantitative correction for nondiffuse properties would be very difficult, but it is clear that the deviation in capsule temperature from that predicted is consistent with the differences in angular emittance (or absorptance) noted.

Temperature vs. distance from the sun.- It was shown in figure 8 that shield temperature may be directly related (by eq. (12)) to distance from the sun if the surface properties of the sunlit side are assumed. Thus, the measured capsule temperature change can also be related to distance from the sun. In figure 11, for example, the sunlit side of the shields in the experiment is assumed to have a white coating and the capsule temperature is calculated on the basis of the experimental results. It is indicated that the shield-capsule configuration studied can approach to within 0.1 A.U. of the sun without reaching excessive temperatures with either of the two different surfaces. Also, even though the aluminum capsule temperature is more than twice as high as predicted, the actual temperature rise is quite small and well within the desired range.

CONCLUDING REMARKS

The experimental results of this program have verified that solar radiation shields are an effective means of minimizing temperature control problems for vehicles subjected to large changes in solar radiation. When compared with these experimental results, it was also shown that, within its assumptions, the radiation heat-transfer analysis previously developed for shield-capsule configurations is satisfactory.

REFERENCES

1. Hall, Charles, F., Nothwang, George J., and Hornby, Harold: A Feasibility Study of Solar Probes. IAS Paper 62-21.

2. Nothwang, George N., Arvesen, John C., and Hamaker, Frank M.: Analysis of Solar-Radiation Shields for Temperature Control of Space Vehicles Subjected to Large Changes in Solar Energy. NASA TN D-1209, 1962.

3. Anderson, Donald L., and Nothwang, George J.: Effects of Sputtering With Hydrogen Ions on Total Hemispherical Emittance of Several Metallic Surfaces. NASA TN D-1646, 1963.

4. Eckert, E. R. G.: Heat and Mass Transfer. Second ed., pt. A, Heat Conduction and Appendix of Property Values by Robert M. Drake, Jr., McGraw-Hill Book Co., Inc., N. Y., 1959, p. 377.

FIGURE LEGENDS

Figure 1.- Basic shield and capsule geometry.

Figure 2.- Photograph of capsule.

Figure 3.- Variation of emittance with viewing angle for carbon-black and aluminum surfaces.

Figure 4.- Photographs of space-environment vacuum chamber.
(a) Vacuum chamber.
(b) Interior of vacuum chamber; capsule installed.

Figure 5.- Schematic of experimental test setup.

Figure 6.- Capsule temperature versus distance from the sun for an unshielded vehicle; no internal heat.

Figure 7.- Theoretical capsule temperature versus distance from the sun for the two surfaces studied (predicted by analysis in ref. 2).

Figure 8.- Theoretical shield temperature versus distance from the sun for shields with various surface properties.

Figure 9.- Temperature of the capsule versus temperature of the shield; black shield and black capsule.

Figure 10.- Temperature of the capsule versus temperature of the shield; aluminum shield and aluminum capsule.

Figure 11.- Predicted capsule temperature versus distance from the sun, based on experimentally determined data.

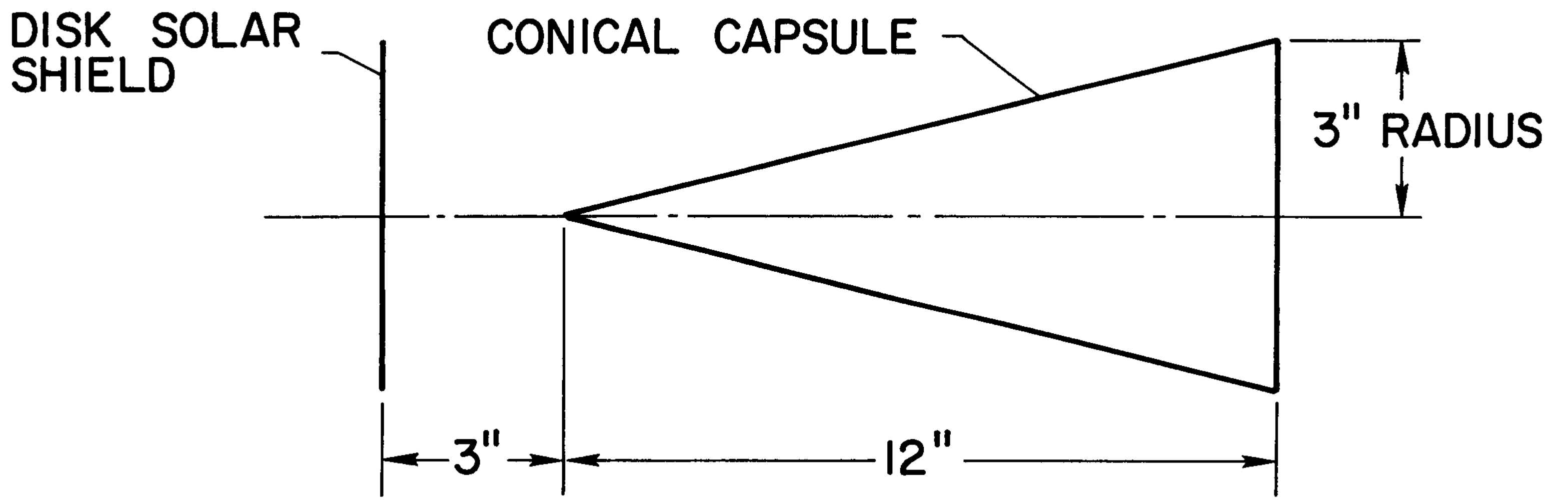
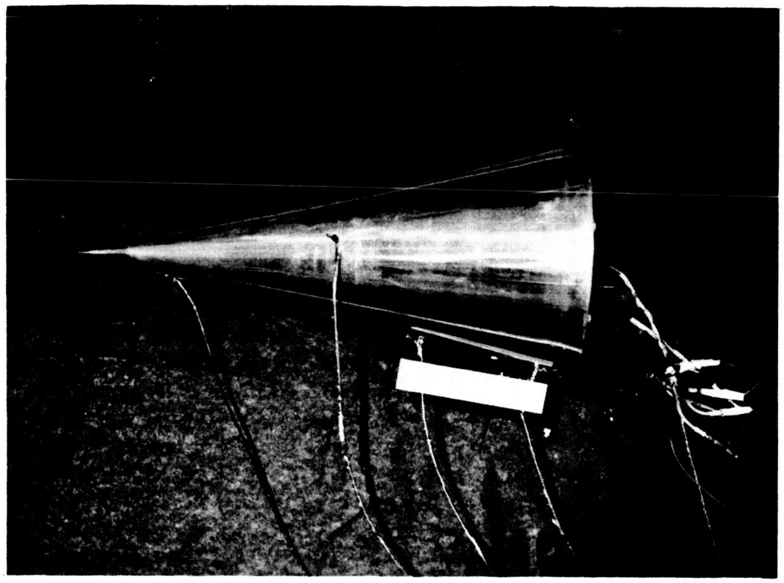


Figure 1.- Basic shield and capsule geometry.



A-30226

Figure 2.- Photograph of capsule.

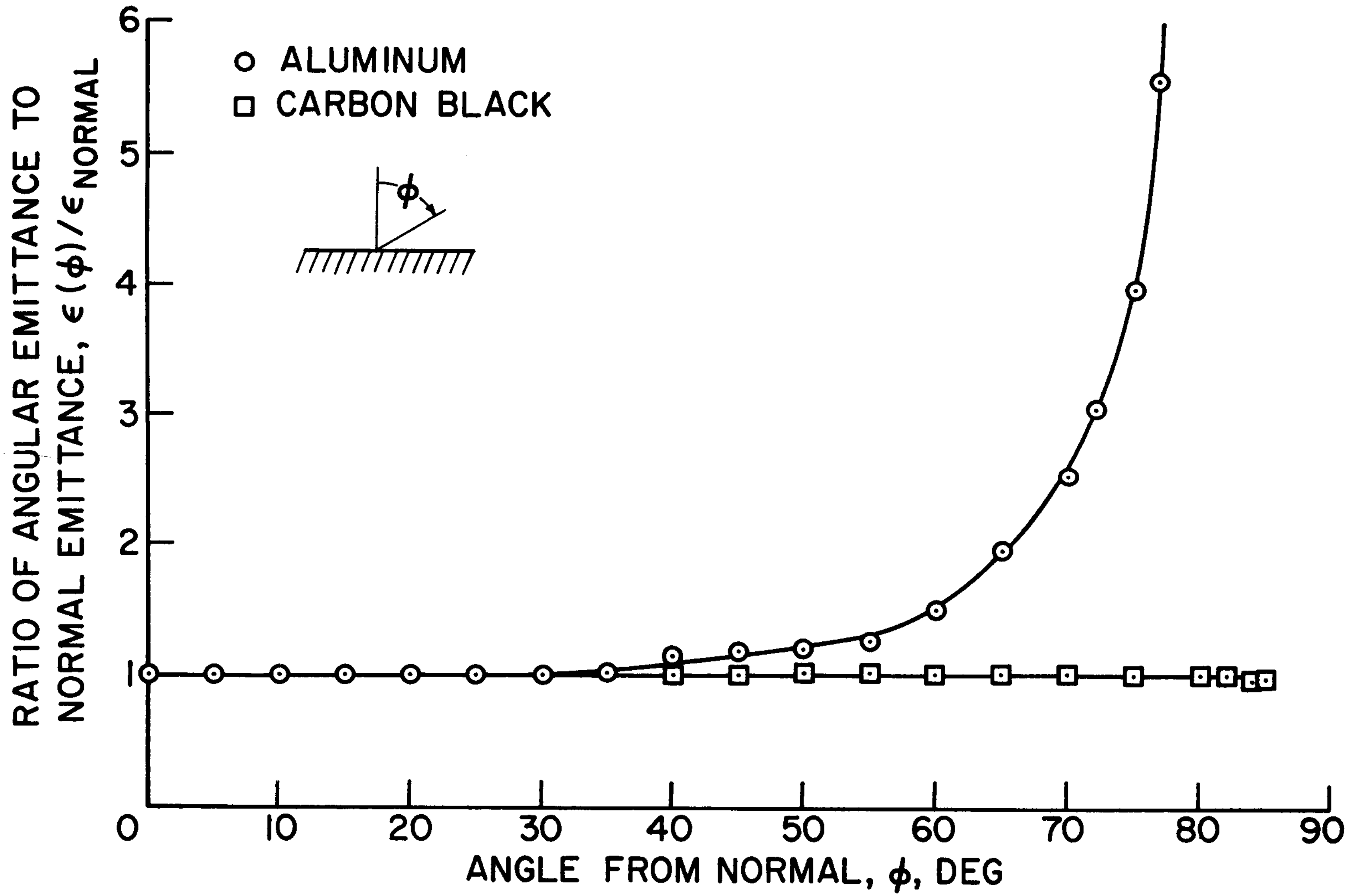
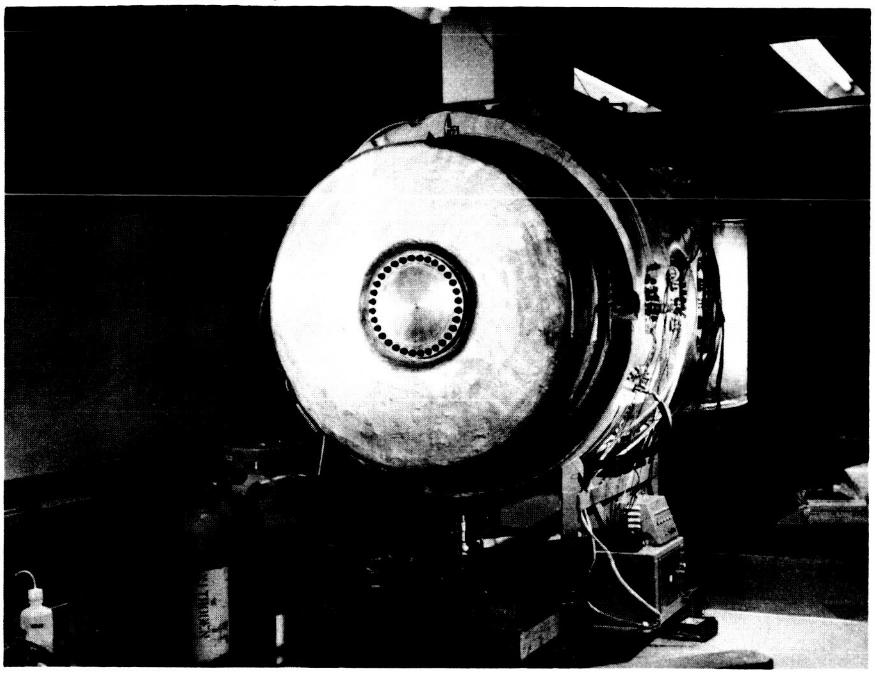


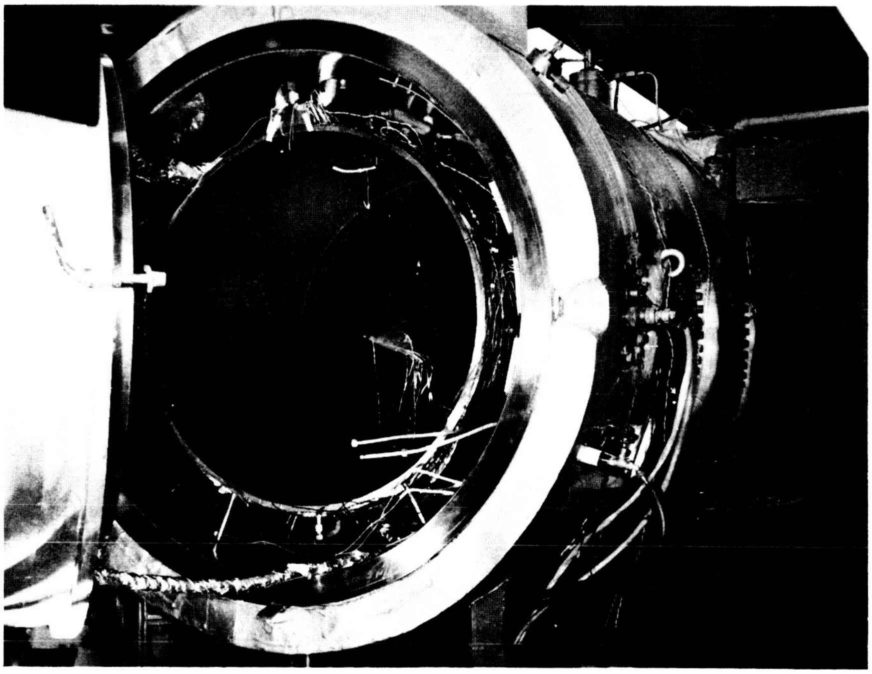
Figure 3.- Variation of emittance with viewing angle for carbon-black and aluminum surfaces.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA



A-30224

(a) Vacuum chamber.



A-30223

(b) Interior of vacuum chamber; capsule installed.

Figure 4.- Photographs of space-environment vacuum chamber.

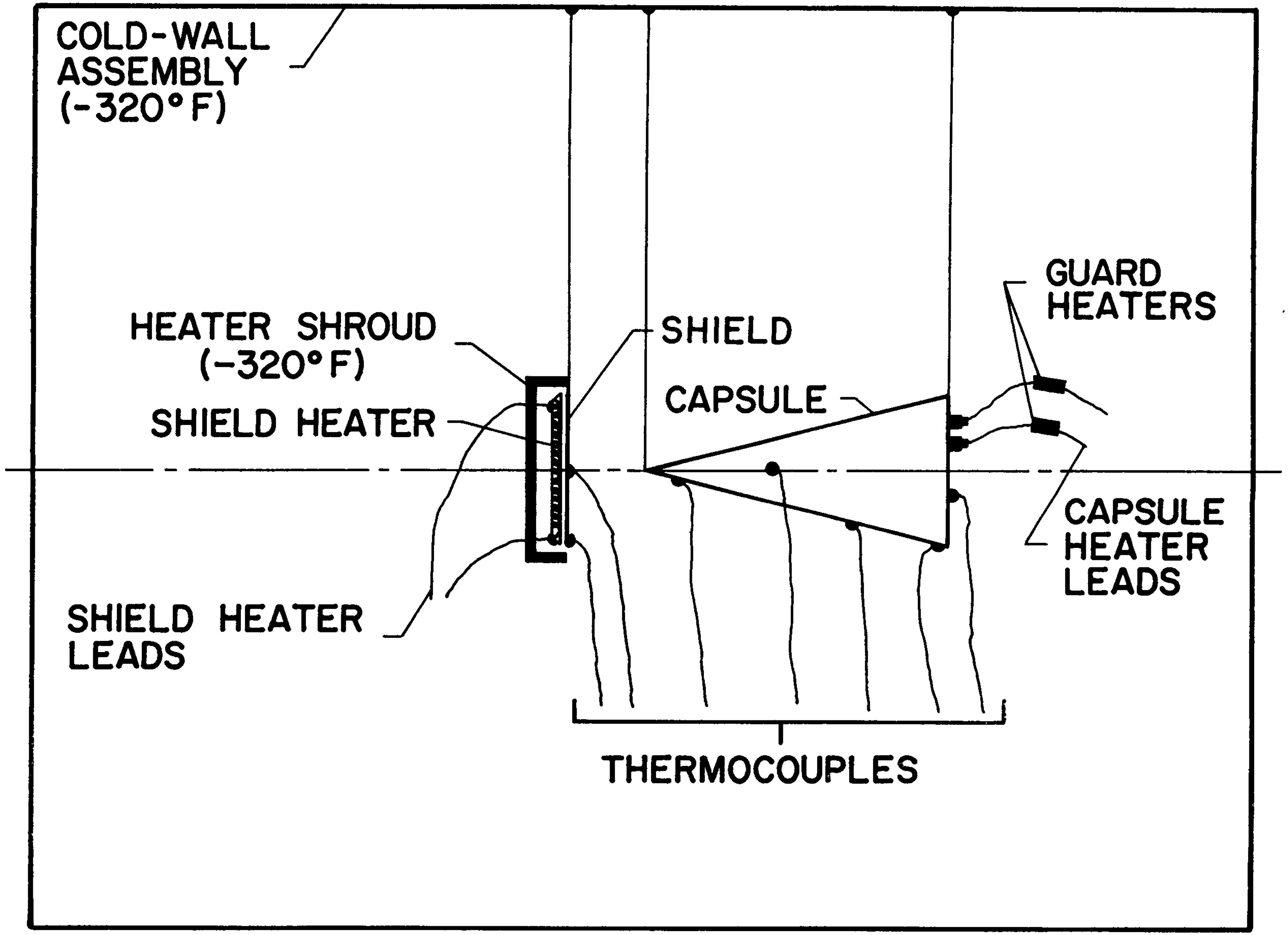


Figure 5.- Schematic of experimental test setup.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

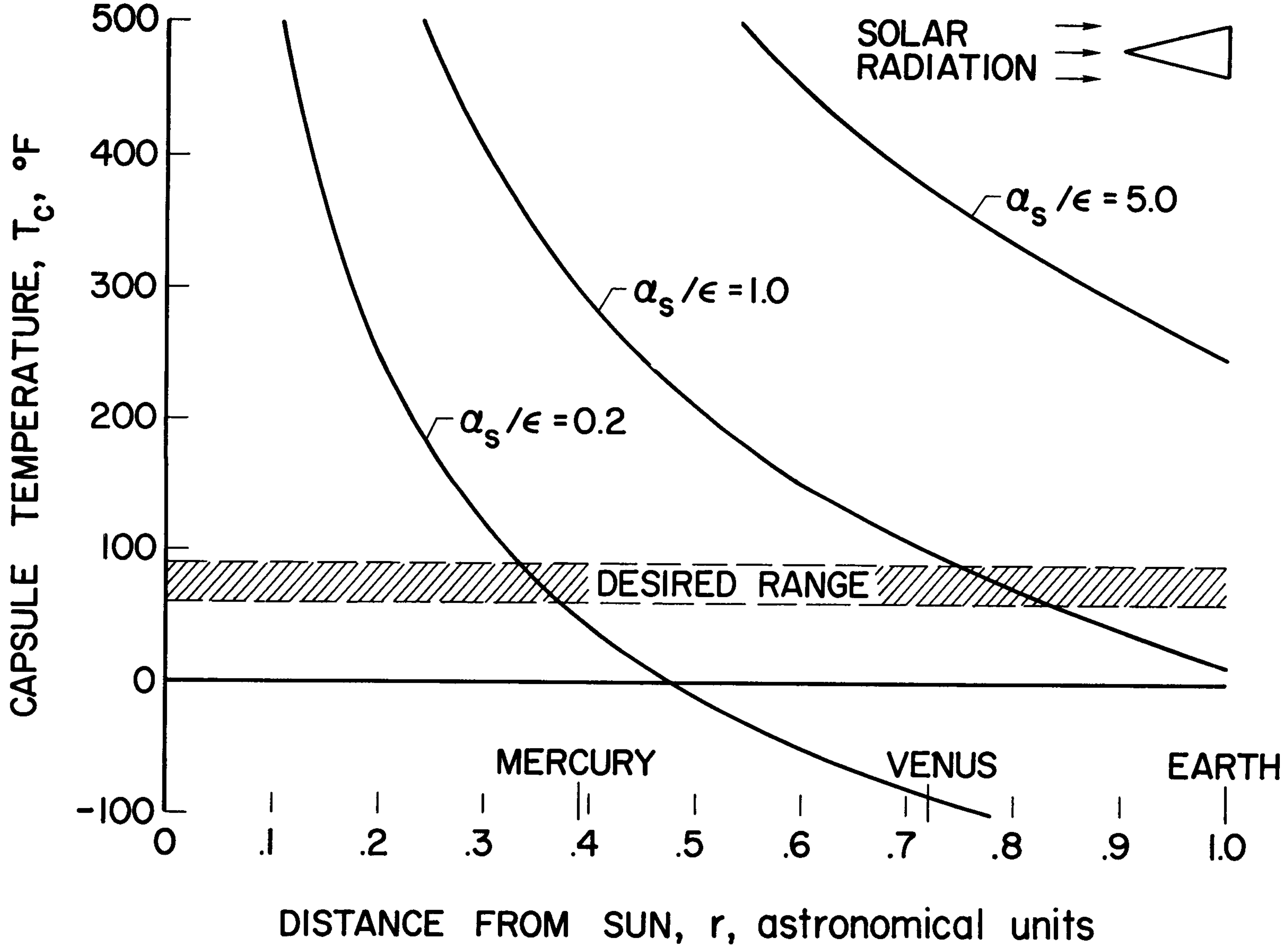


Figure 6.- Capsule temperature versus distance from the sun for an unshielded vehicle; no internal heat.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

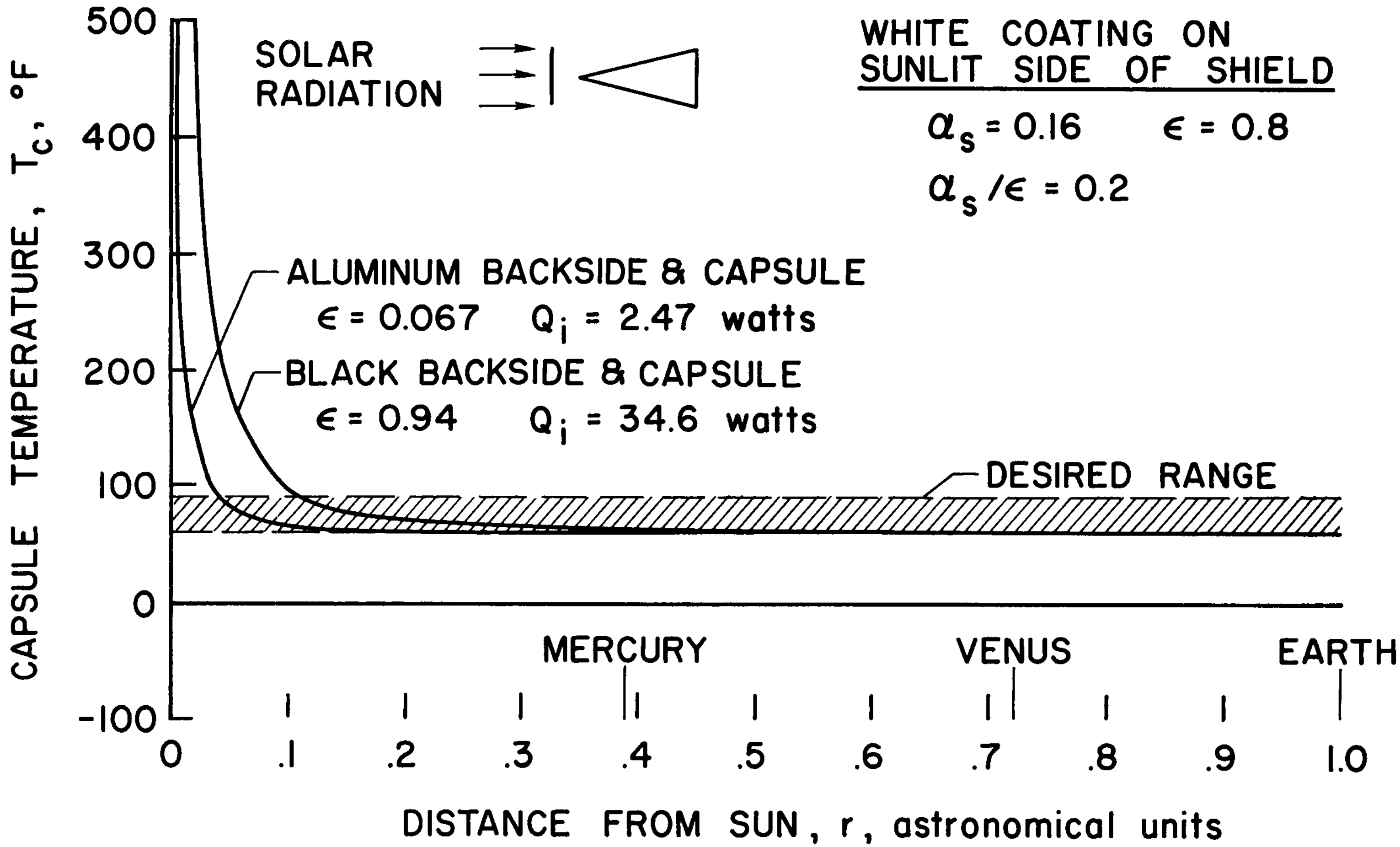


Figure 7.- Theoretical capsule temperature versus distance from the sun for the two surfaces studied (predicted by analysis in ref. 2).

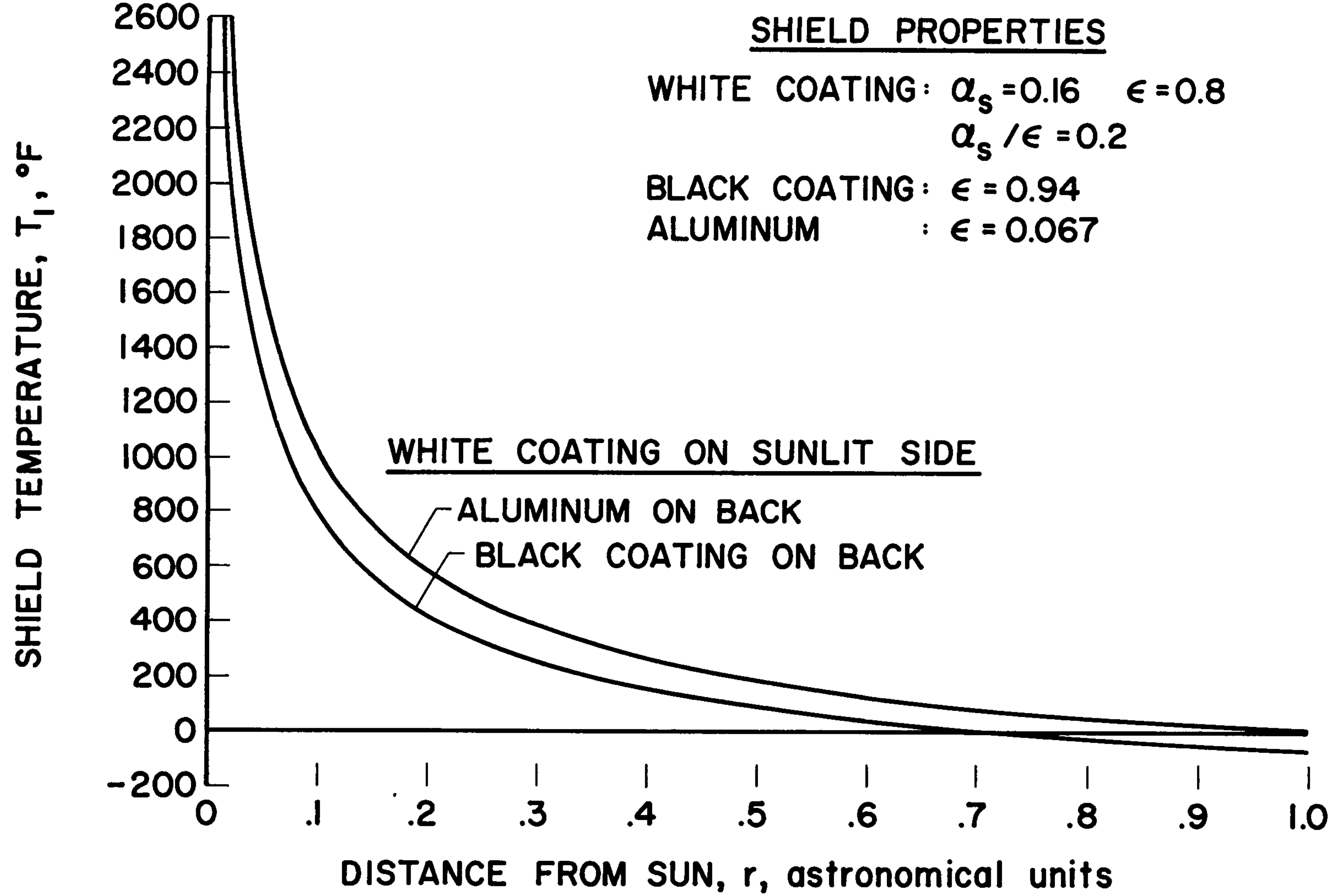


Figure 8.- Theoretical shield temperature versus distance from the sun for shields with various surface properties.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

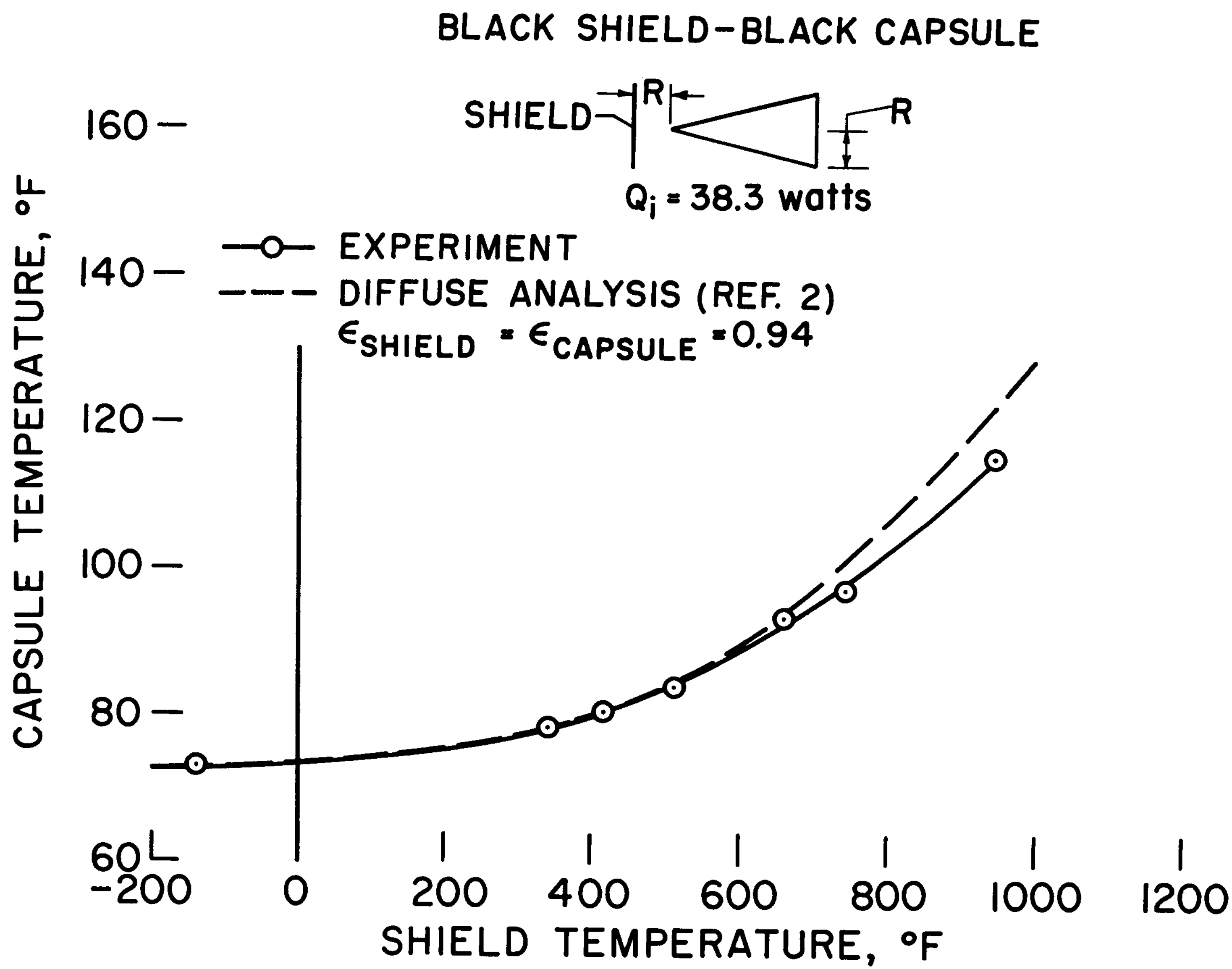


Figure 9.- Temperature of the capsule versus temperature of the shield; black shield and black capsule.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

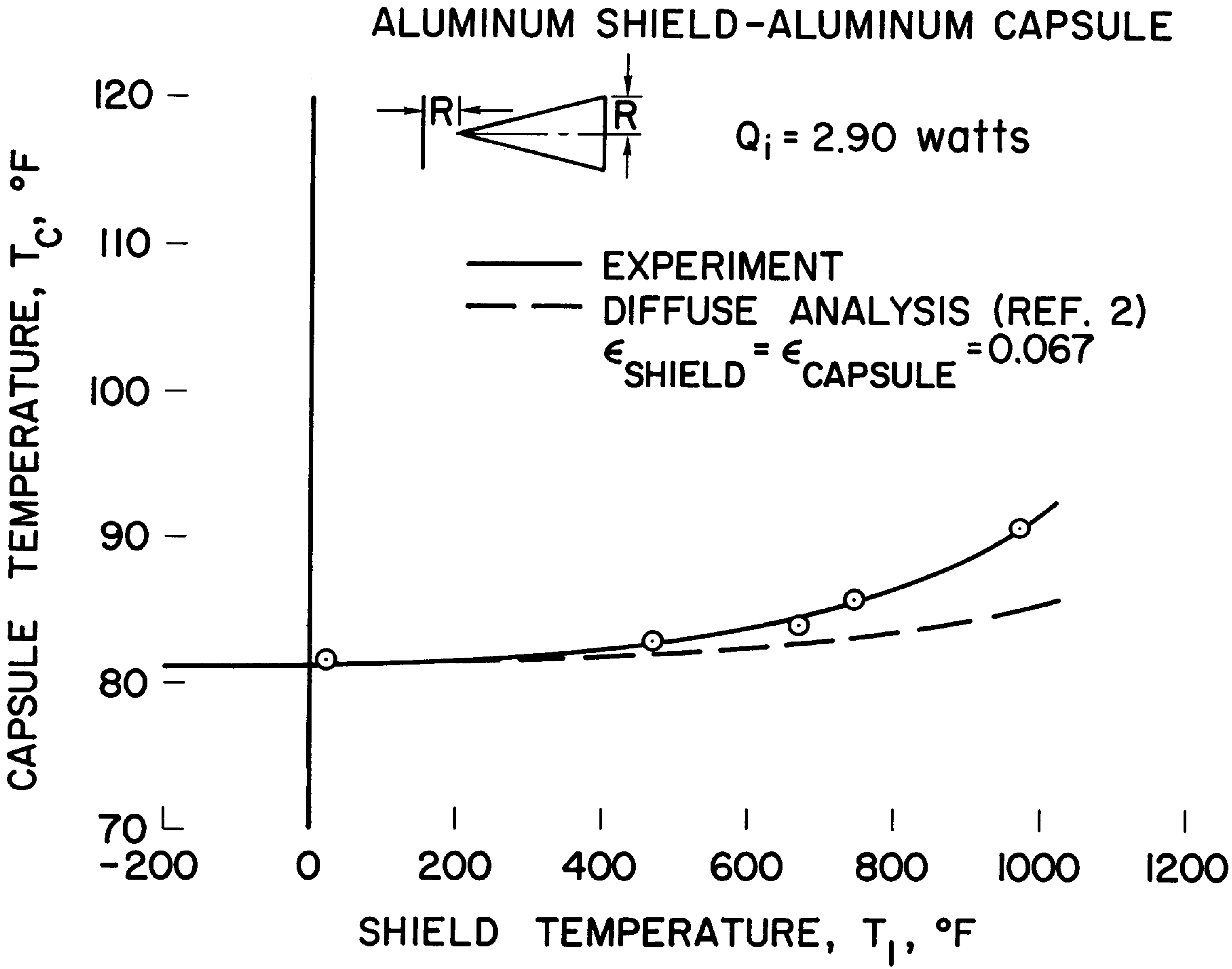


Figure 10.- Temperature of the capsule versus temperature of the shield; aluminum shield and aluminum capsule.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

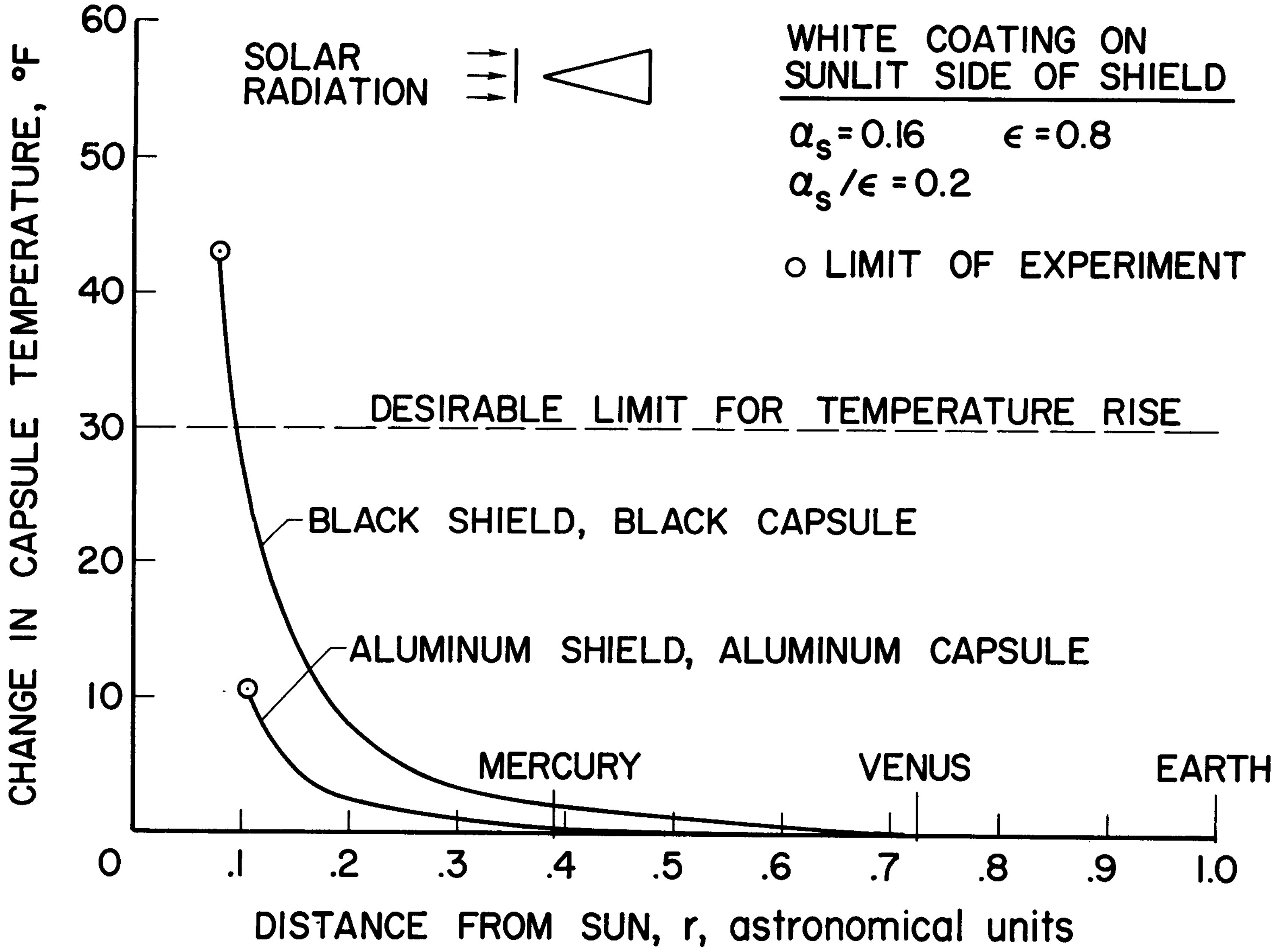


Figure 11.- Predicted capsule temperature versus distance from the sun, based on experimentally determined data.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA